Modelling of Multi-Parameter-Level Simulation Data to Create an Enhanced Cordier Diagram for Radial Turbocompressors

iSimT-24 Symposium on Innovative Simulations in Turbomachinery

Yannick Lattner, M.Eng

Team Lead CFD at ITB Ingenieurgesellschaft für technische Berechnungen

1. Introduction
2. Computational Model
3. Nested Design of Experiments
4. Surrogate Modeling
5. Applications

INTRODUCTION

Parameterization, simulation and data-modeling as an integral part of the PhD-thesis:

A Multi-Level Design Space-Based

Enhanced Cordier Diagram for Radial Turbocompressors

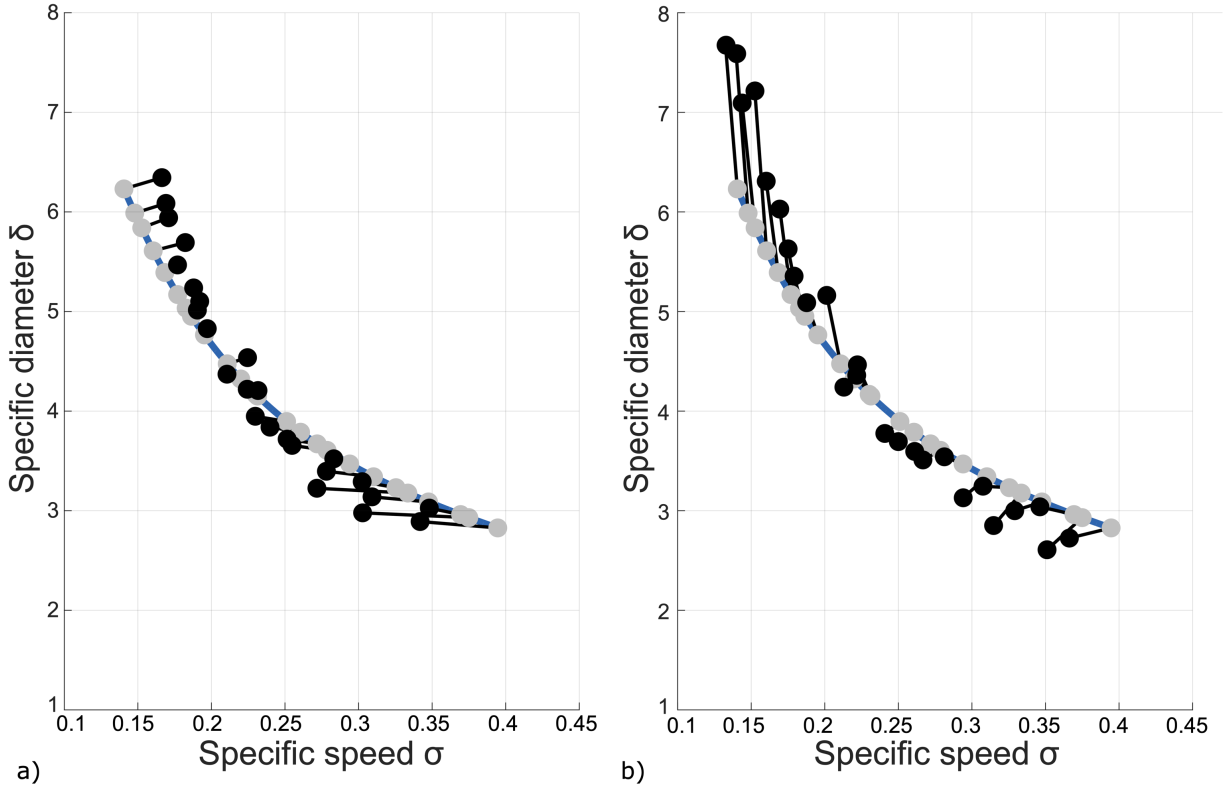
(Currently being reviewed at Bauhaus-Universität Weimar)

INTRODUCTION

Concept of the enhanced Cordier diagram

The Cordier diagram

- Shall provide combinations of specific speed σ and specific diameter δ using the Cordier line
- Iterations of rotational velocity or diameter to obtain feasible designs, change the location in the Cordier diagram
- Cordier line is not a functional, precise approach for modern radial turbocompressor designs

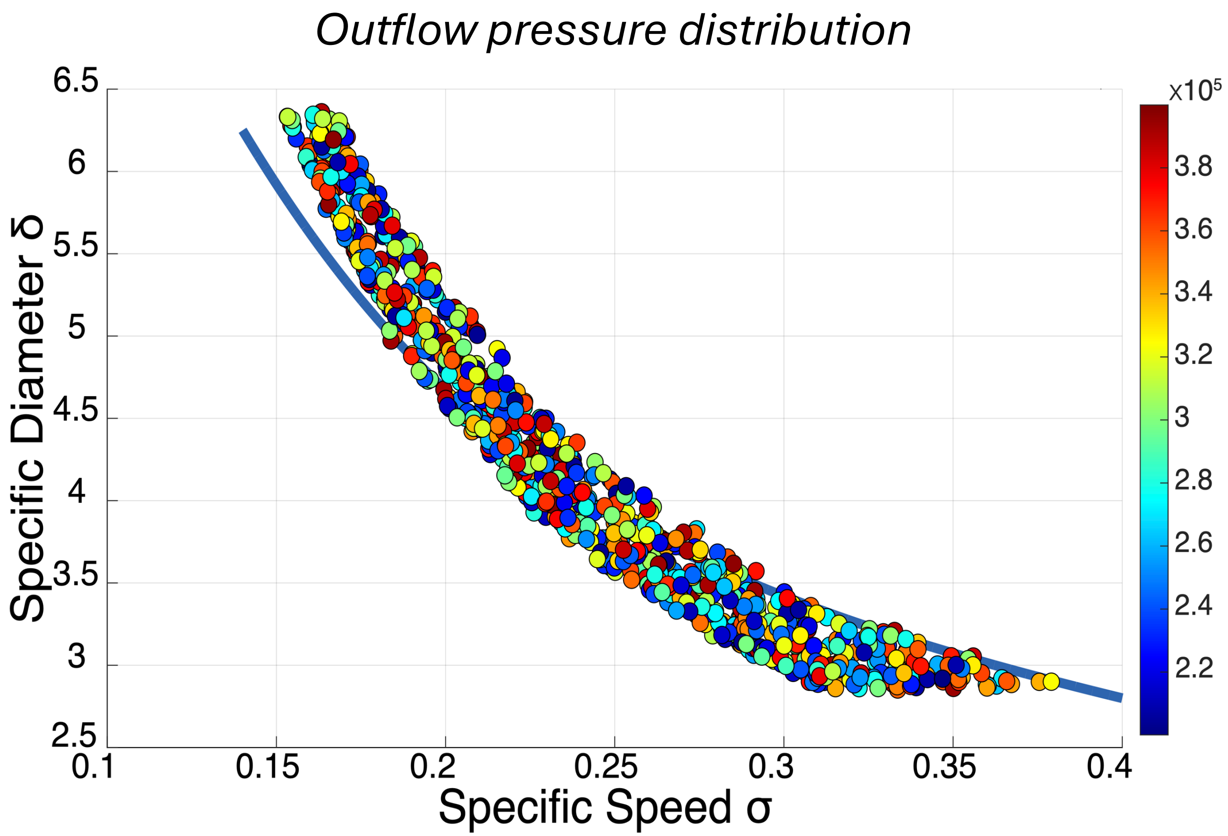


INTRODUCTION

Concept of the enhanced Cordier diagram

The Cordier diagram

- Shall provide combinations of specific speed σ and specific diameter δ using the Cordier line
- Iterations of rotational velocity or diameter to obtain feasible designs, change the location in the Cordier diagram
- Cordier line is not a functional, precise approach for modern radial turbocompressor designs



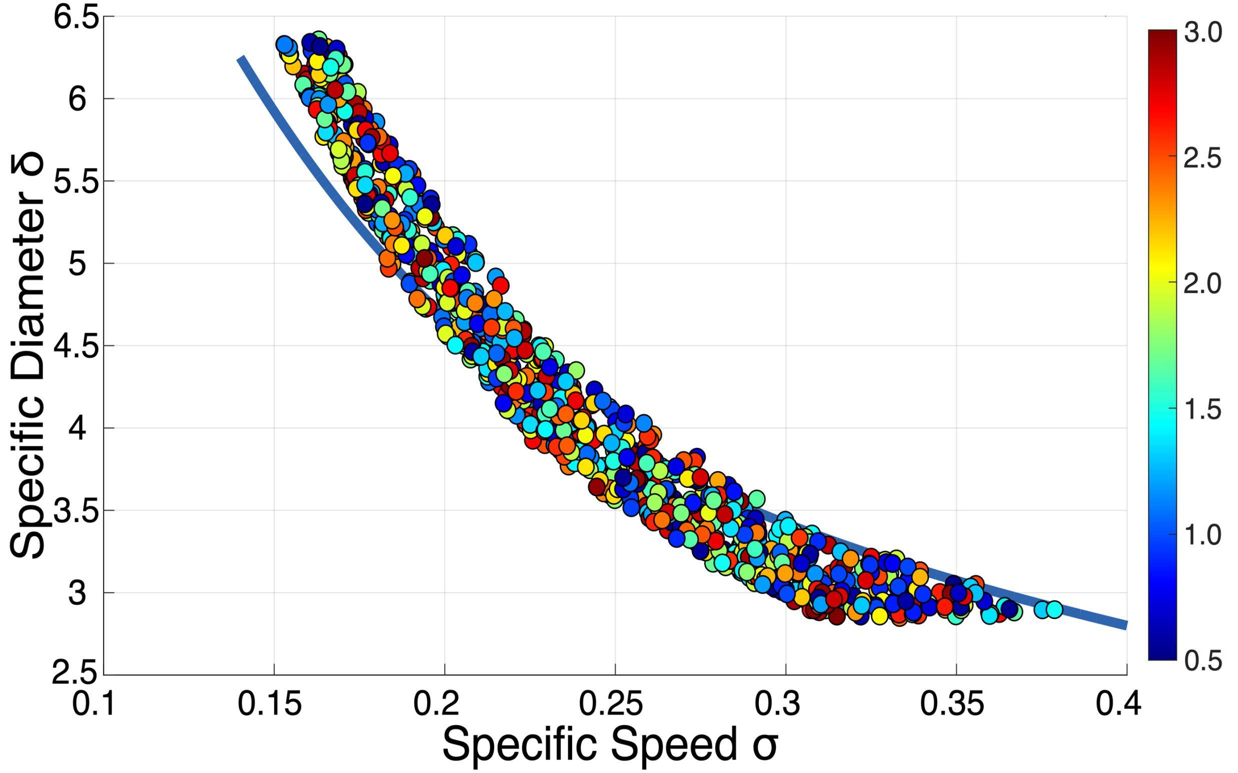
INTRODUCTION

Concept of the enhanced Cordier diagram

The Cordier diagram

- Shall provide combinations of specific speed σ and specific diameter δ using the Cordier line
- Iterations of rotational velocity or diameter to obtain feasible designs, change the location in the Cordier diagram
- Cordier line is not a functional, precise approach for modern radial turbocompressor designs

Ambient volume flow distribution

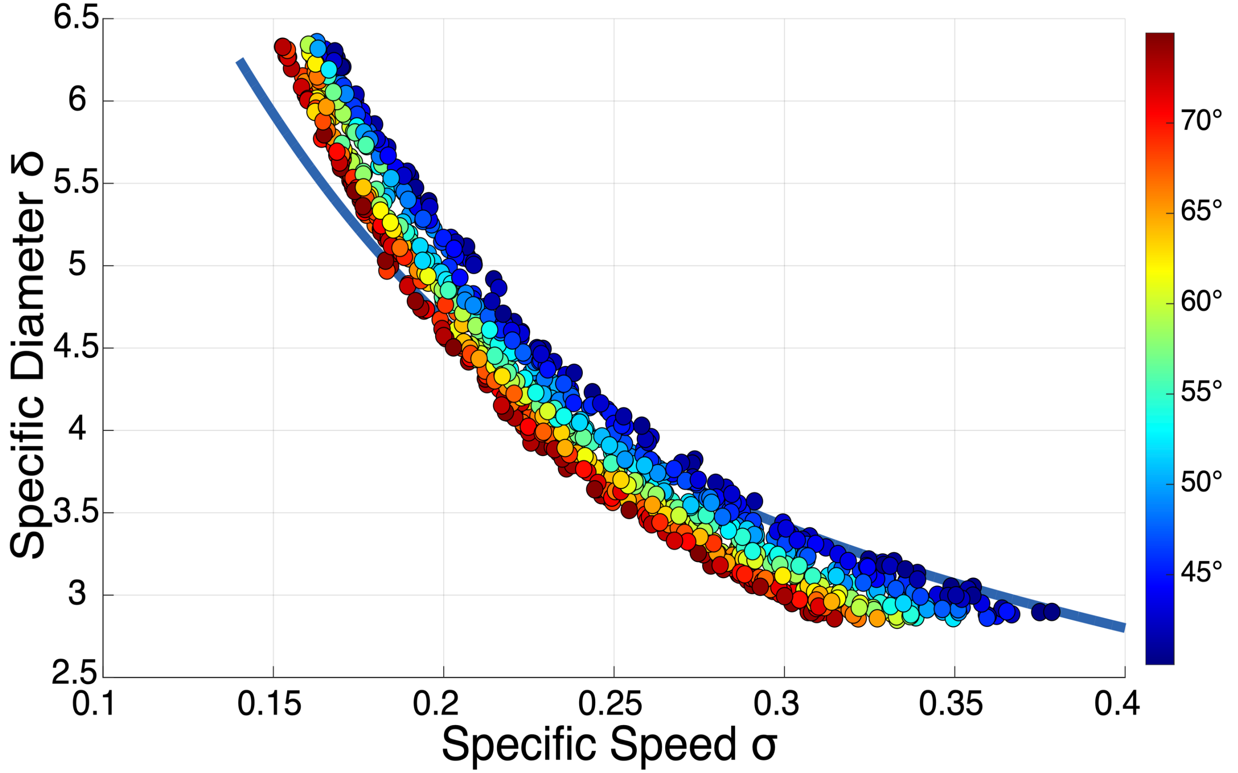


Concept of the enhanced Cordier diagram

The Cordier diagram

- Shall provide combinations of specific speed σ and specific diameter δ using the Cordier line
- Iterations of rotational velocity or diameter to obtain feasible designs, change the location in the Cordier diagram
- Cordier line is not a functional, precise approach for modern radial turbocompressor designs

Impeller exit relative blade angle distribution

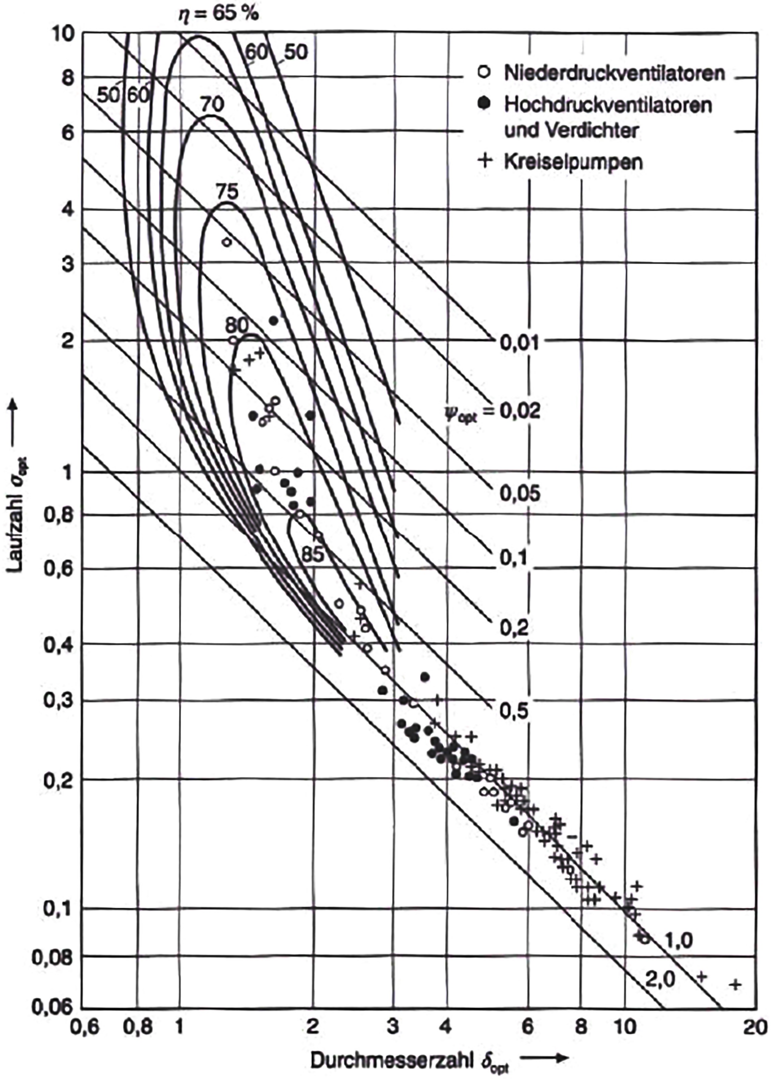


INTRODUCTION

Concept of the enhanced Cordier diagram

The Cordier diagram

- Fails to provide precise combinations of rotational velocity and impeller diameter for modern machines
- Does not provide any indication regarding a future compressor's efficiency
- Neglects significant parameter influences



INTRODUCTION

Concept of the enhanced Cordier diagram

A digital, enhanced Cordier Diagram

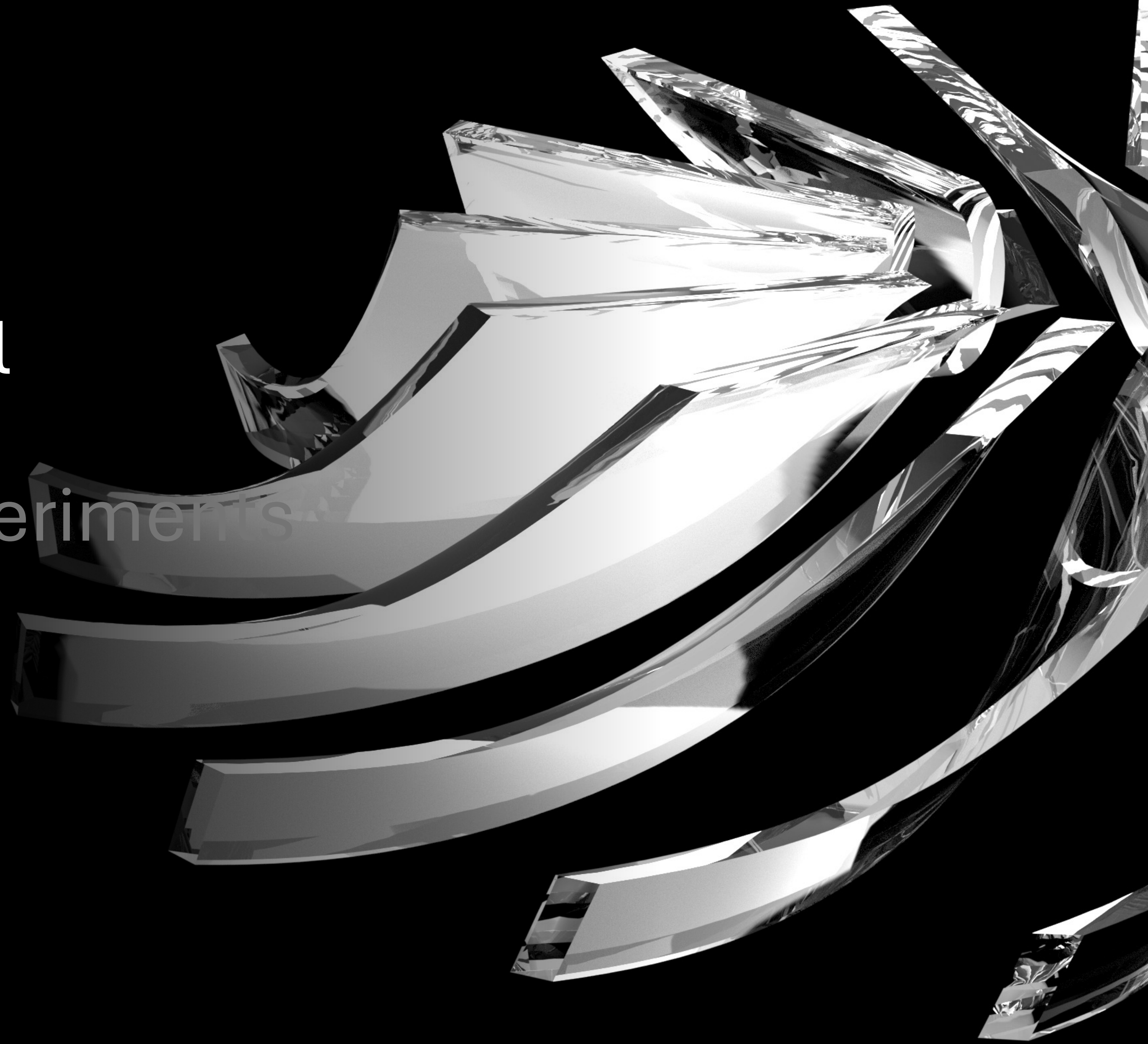
- Re-enable the indented use
- Provide addition data to weight possible designs
- Operate as a digital tool with application-based outputs
- **Based on simulation data of modern radial turbocompressors**
- Inputs must be available at the start of the design process

INTRODUCTION

Requirements to the computational model

- Complex parameter space
  - Differentiation of influences introduced by geometry design space and machine design space
  - Machine design process
  - Parameterized CAD Geometry
  - CFD-based speed line computation
  - Structural simulation (FEA)
- Automated workflow
- Compatible parameter spaces

1. Introduction
2. **Computational Model**
3. Nested Design of Experiments
4. Surrogate Modeling
5. Applications



COMPUTATIONAL MODEL

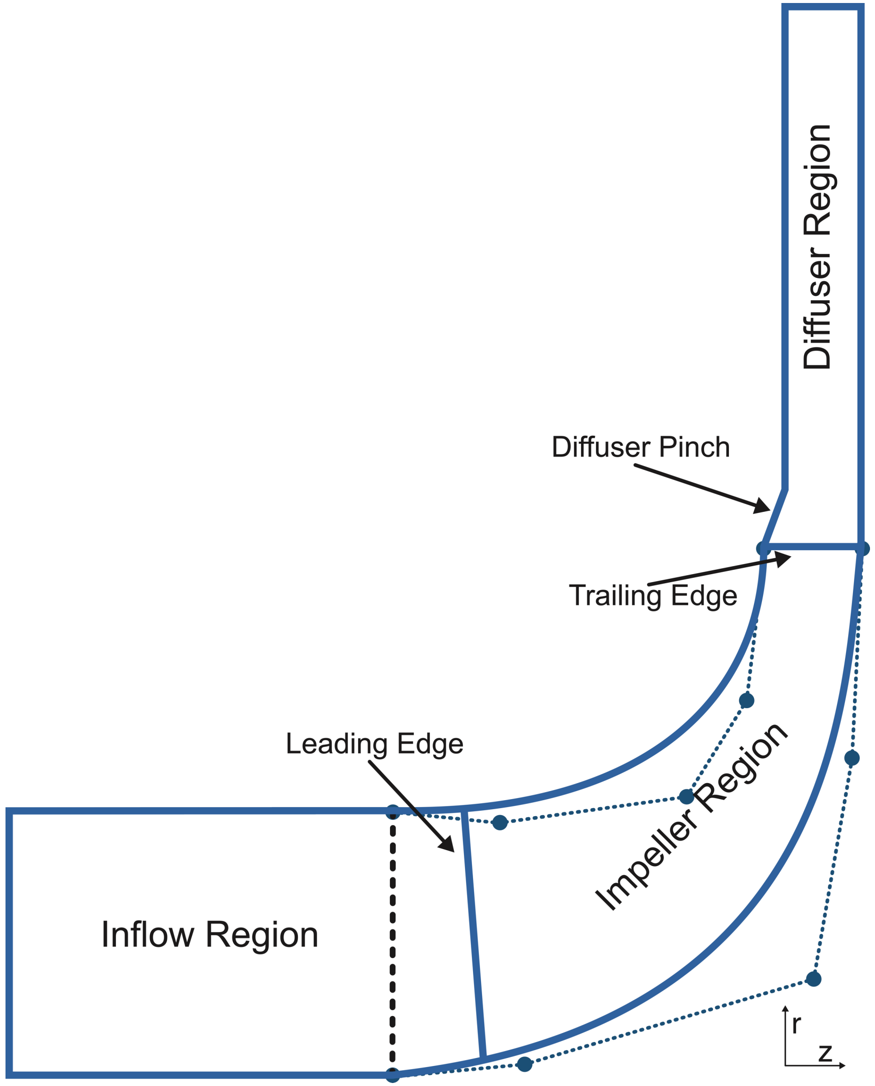
Machine Design Model

- Inputs:
  - Ambient conditions
  - Outflow pressure
  - Ambient volume flow
  - Axial impeller extent ratio
  - Impeller exit relative blade angle
  - Circumferential blade extent
  - Number of blades
  - …
- Outputs:
  - All principal dimensions
    - Diameters
    - Blade angles
    - Thermodynamic properties
    - Chord Reynolds number
    - …

COMPUTATIONAL MODEL

Geometry Design

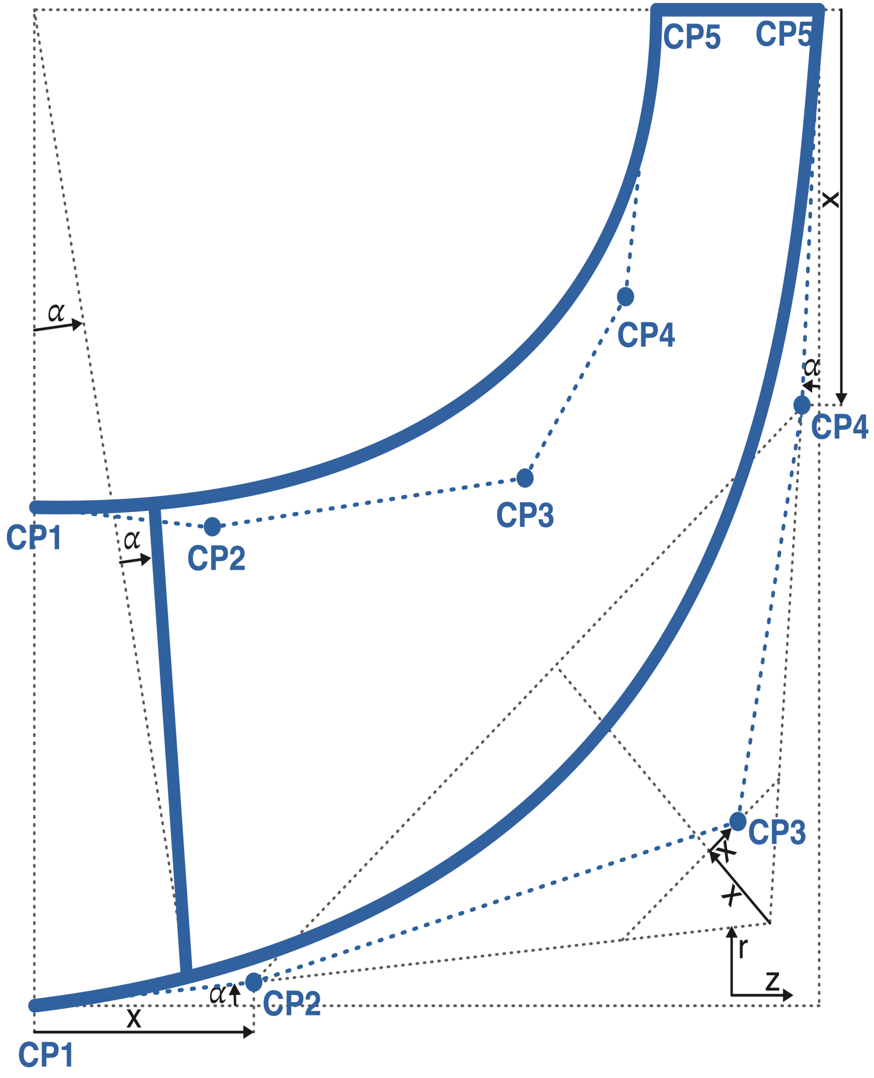
- Based on non-dimensional parameters (Angles / ratio to D_2)
- Including parameterized impeller disc
- Reduced parameter set controls multiple design parameters by global parameters



COMPUTATIONAL MODEL

Geometry Design

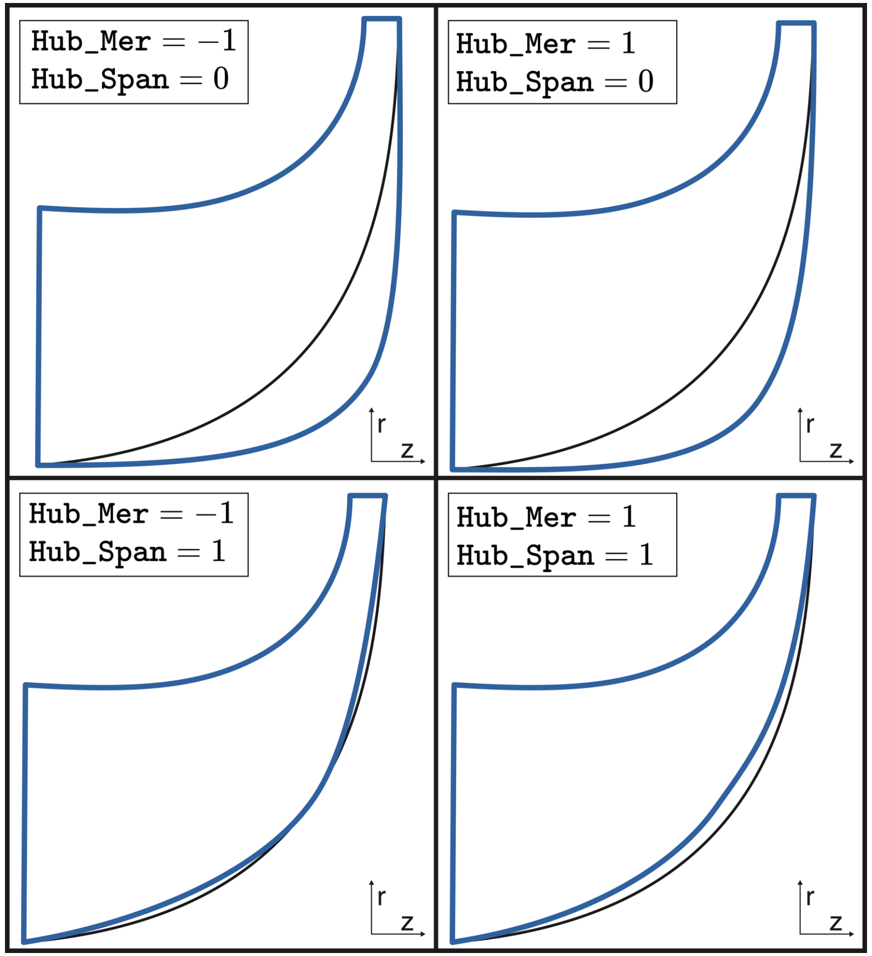
- Based on non-dimensional parameters (Angles / ratio to D_2)
- Including parameterized impeller disc
- Reduced parameter set controls multiple design parameters by global parameters



COMPUTATIONAL MODEL

Geometry Design

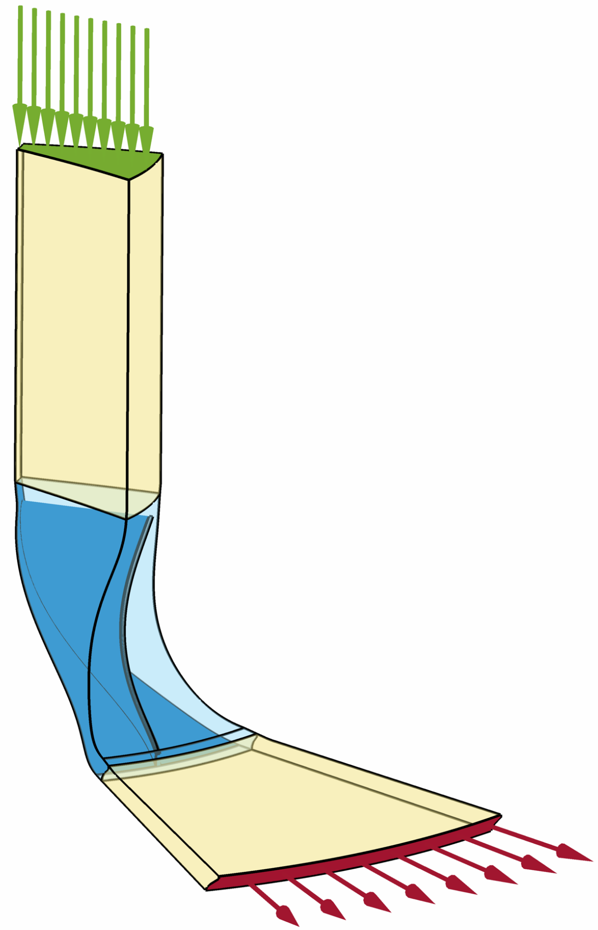
- Reduced parameter set controls multiple design parameters by global parameters
- Allows for significant reduction of sample size with neglectable reduction of result parameter range



COMPUTATIONAL MODEL

CFD Model

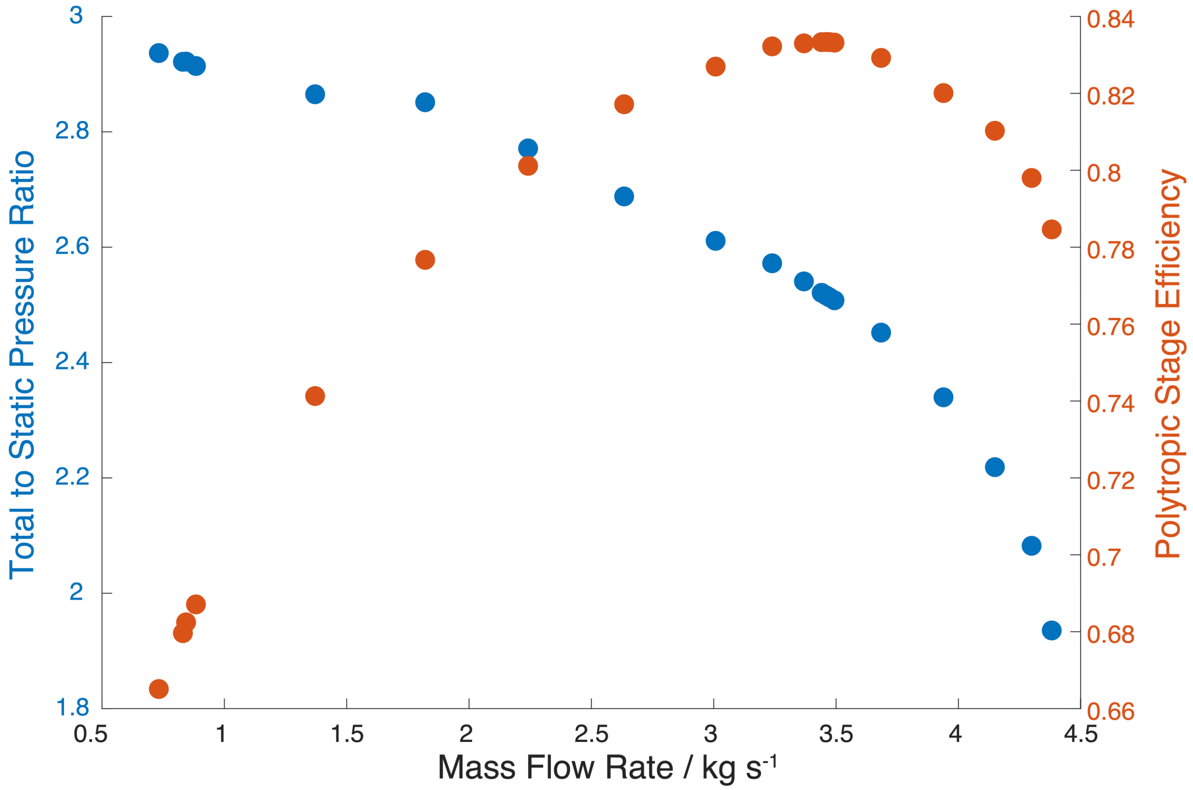
- CFX Turbomachinery Setup
- Exit-corrected mass flow rate
- Convergence evaluation using CoV
- Averaging approach for unsteady results



COMPUTATIONAL MODEL

Speed Line Computation

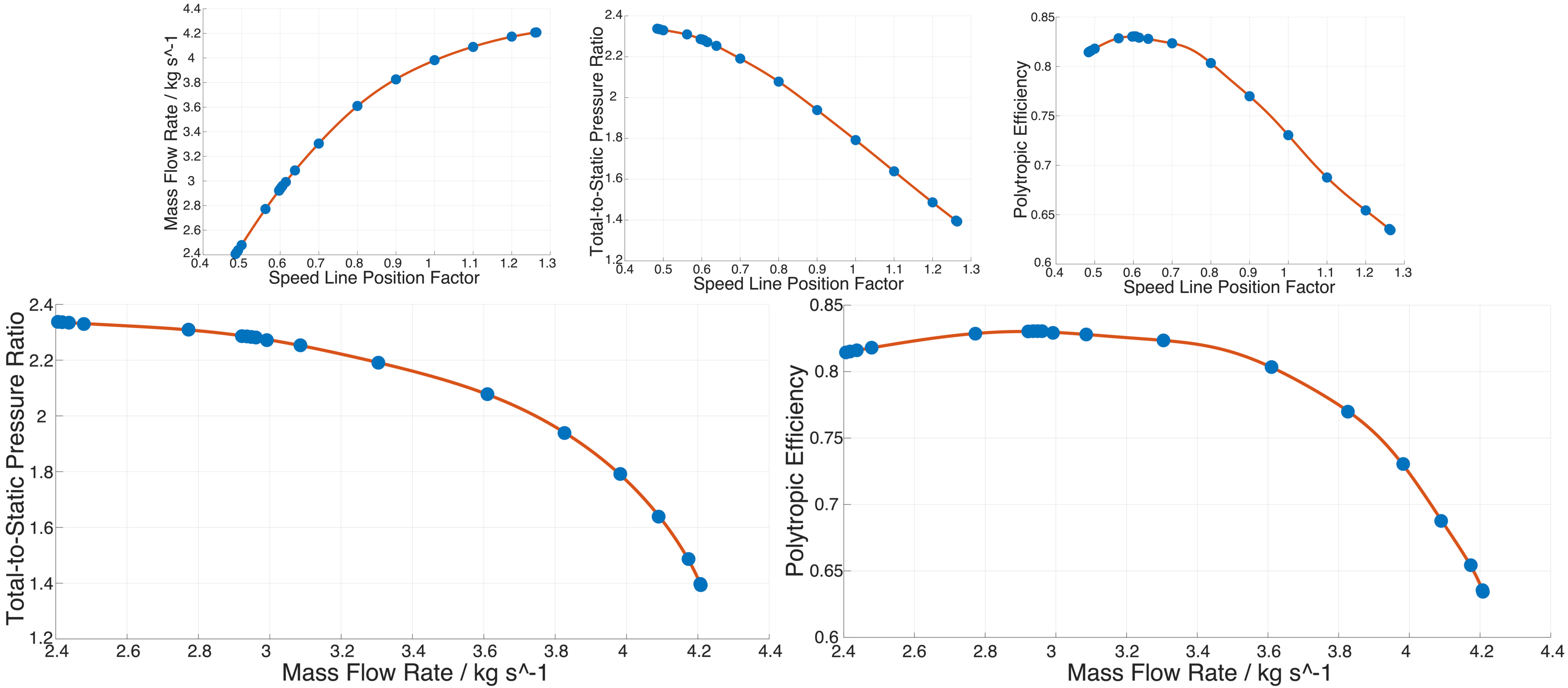
- Fully automated speed line computation tool [1)]
- Choke point defined at quasi-constant mass flow rate
- Surge at maximum of static outflow pressure
- Direct Peak-Efficiency point identification



[1)] "Physics-Based Surge Point Identification for Unsupervised CFD-Computation of Centrifugal Compressor Speed Lines" in Energy Conversion and Management: X, Yannick Lattner, Marius Geller and Michael Kutz, DOI: 10.1016/j.ecmx.2022.100337

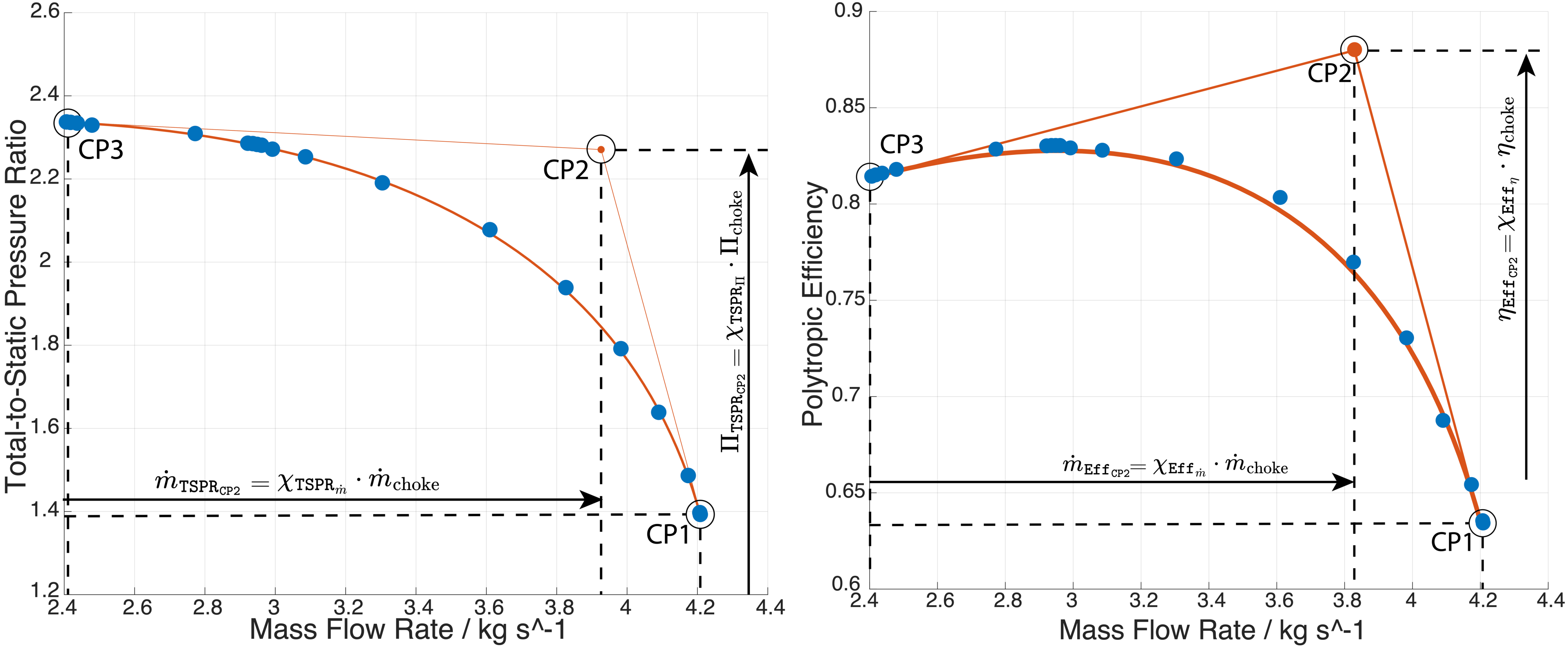
COMPUTATIONAL MODEL

Neural network-based speed Line interpolation



COMPUTATIONAL MODEL

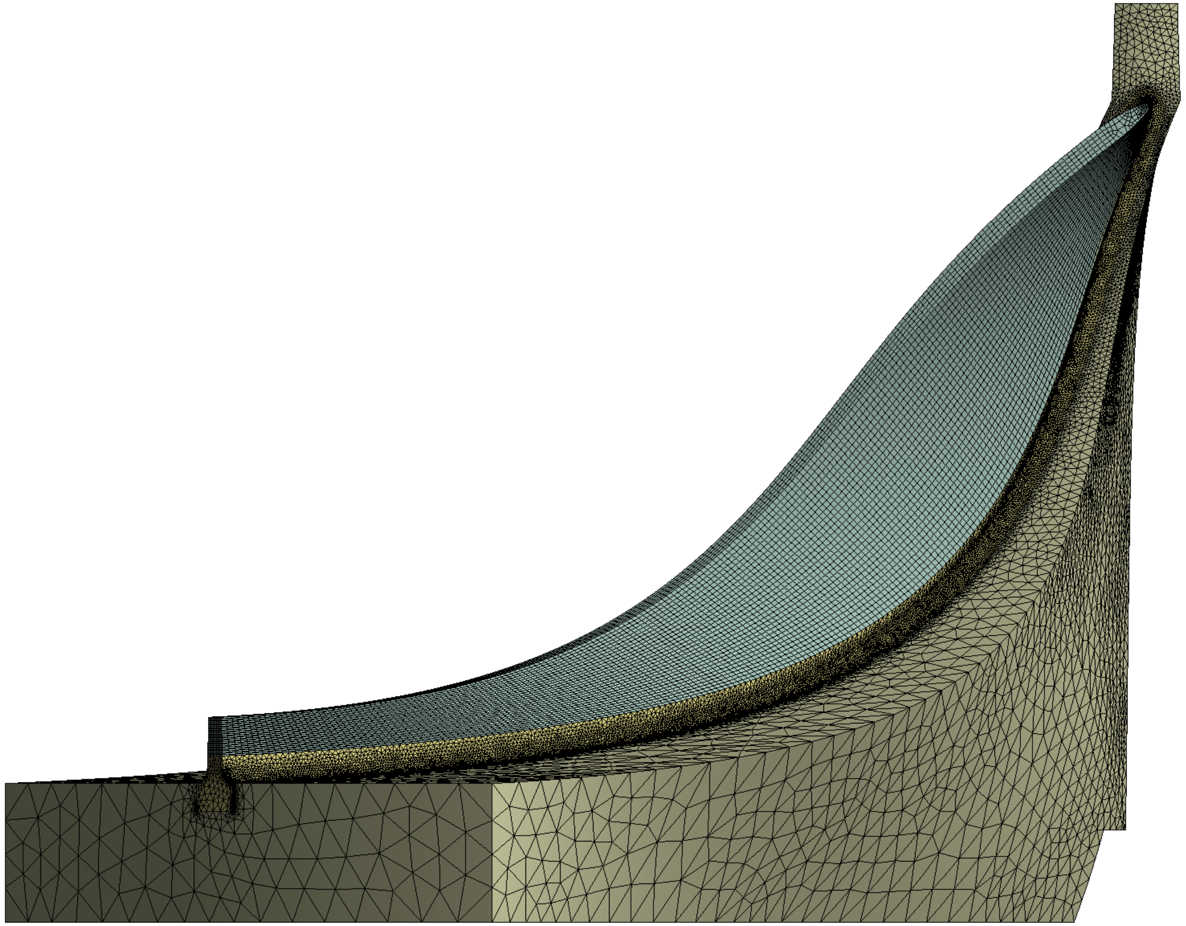
Low order, Bézier spline-based speed Line approximation model



COMPUTATIONAL MODEL

FEA Model

- Load due to rotational velocity
- No thermal or dynamic effects
- Evaluation of:
  - Maximum deformation and von-Mises stress
  - Leading and trailing edge deformations
  - Elastic strain energy (density) for multiple partitions



COMPUTATIONAL MODEL

Hybrid Surrogate modeling

- Flexible and universal approach to surrogate modeling using multiple component surrogate models (CSMs)
- Each component surrogate model is individually trained
- Hybrid surrogate model is composed by all by optimizing individual weights
- In this approach, combination of:
  - Polynomial regression
  - Neural networks
  - Kriging

COMPUTATIONAL MODEL

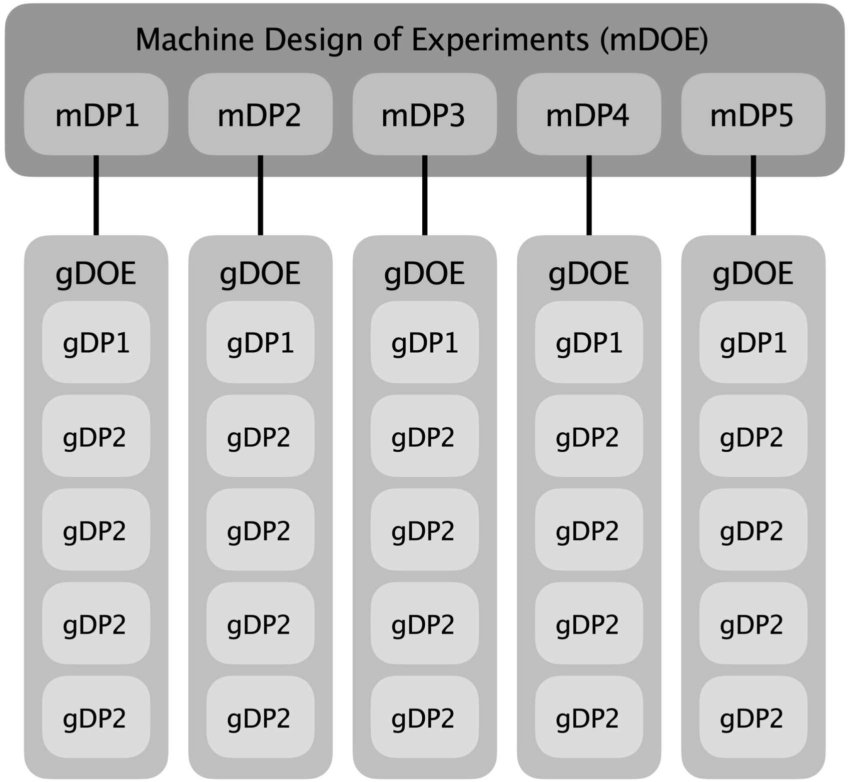
Hybrid Surrogate modeling

- Scanning-test-set cross validation
- Measure for surrogate modeling
  - WR2: Weighted coefficient of determination:

$$WR2 = 1 - \frac{SSE_{\text{Test}} + \alpha SSE_{\text{Training}}}{SST_{\text{Test}} + \alpha SST_{\text{Training}}}$$

NESTED DESIGN OF EXPERIMENTS

- Separation of machine design space and geometry design space
- First level: machine design of experiments
- Second level: geometry designs of experiments for each machine design

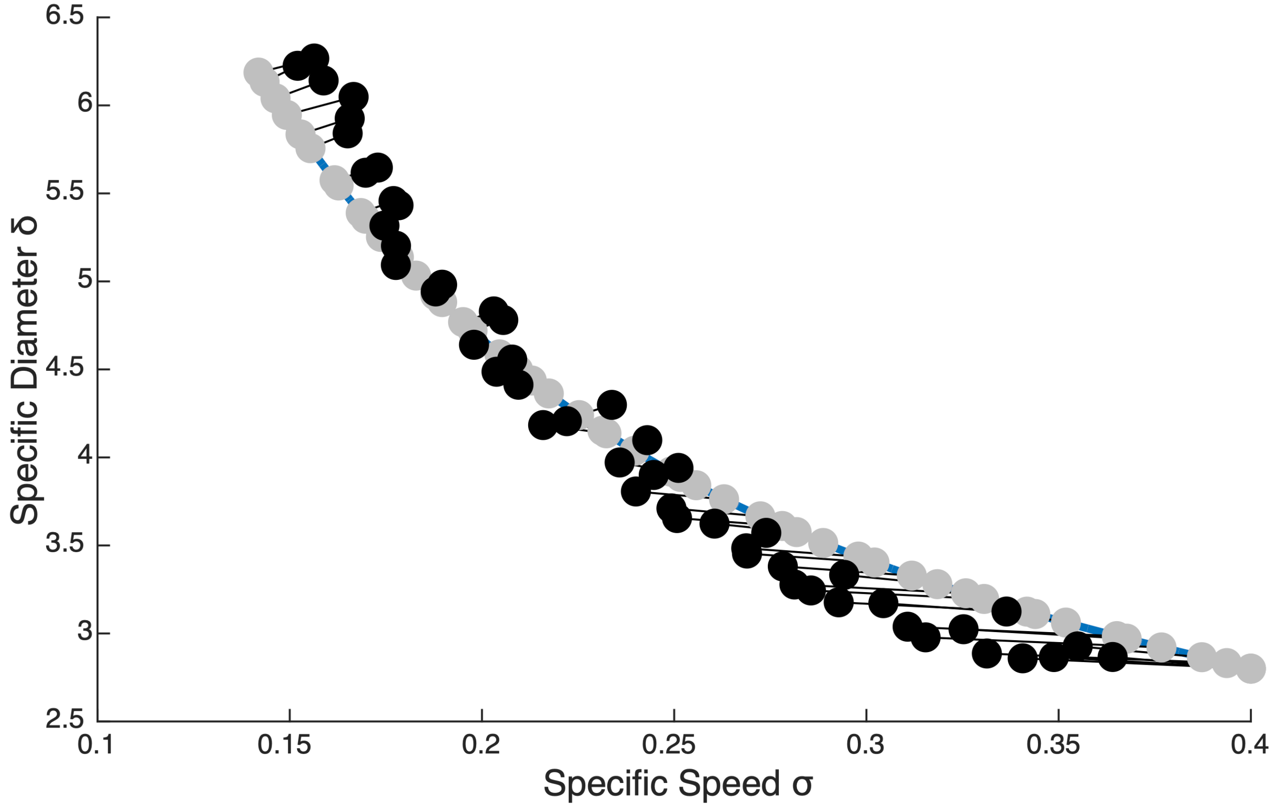


NESTED DESIGN OF EXPERIMENTS

Machine design of experiments

- 50 Machine designs using LHS design

Parameter	Symbol	DOE Properties
Sampled properties		*Range*
Cordier line position	s_{CORDIER}	0 to 1
Outflow pressure	p_{out}	2×10^5 Pa to 4×10^5 Pa
Ambient volume flow rate	$\dot{V}_{\text{amb}}$	$0.5\,\text{m}^3\,\text{s}^{-1}$ to $4\,\text{m}^3\,\text{s}^{-1}$
Axial impeller extent ratio	ν_L	0.2 to 0.4
Trailing edge blade angle	β_2	40° to 75°
Circumferential blade extent	θ_2	35° to 55°
Constant properties		*Value*
Ambient pressure	p_{amb}	1×10^5 Pa
Ambient temperature	T_{amb}	288.15 K
Hub to shaft diameter ratio	$D_{1_{\text{hub}}}/D_{\text{shaft}}$	1.25
Blade thickness ratio	ν_s	0.01
Number of blades	z	13



NESTED DESIGN OF EXPERIMENTS

Geometry design of experiments

- 50 geometry designs using LHS design for each machine design point

Parameter	Symbol	DOE Properties
Sampled properties		*Range*
Hub control points in meridional direction	`Hub_Mer`	-1 to 1
Hub control points in spanwise direction	`Hub_Span`	0 to 1
Shroud control points in meridional direction	`Shroud_Mer`	-1 to 1
Shroud control points in spanwise direction	`Shroud_Span`	0 to 1
Leading edge hub position	`LE_Hub_Pos`	0.05 to 0.15
Leading edge offset angle hub to shroud	`LE_Shroud_Offset`	$0°$ to $10°$
Blade twist (Leading Edge)	`Twist`	$-10°$ to $10°$
Blade rake (Trailing Edge)	`Rake`	$-25°$ to $25°$
Intensity of blade's S-shape (*hub*)	`Theta_Hub_S`	0 to 1
Intensity of blade's S-shape (*shroud*)	`Theta_Shroud_S`	0 to 1

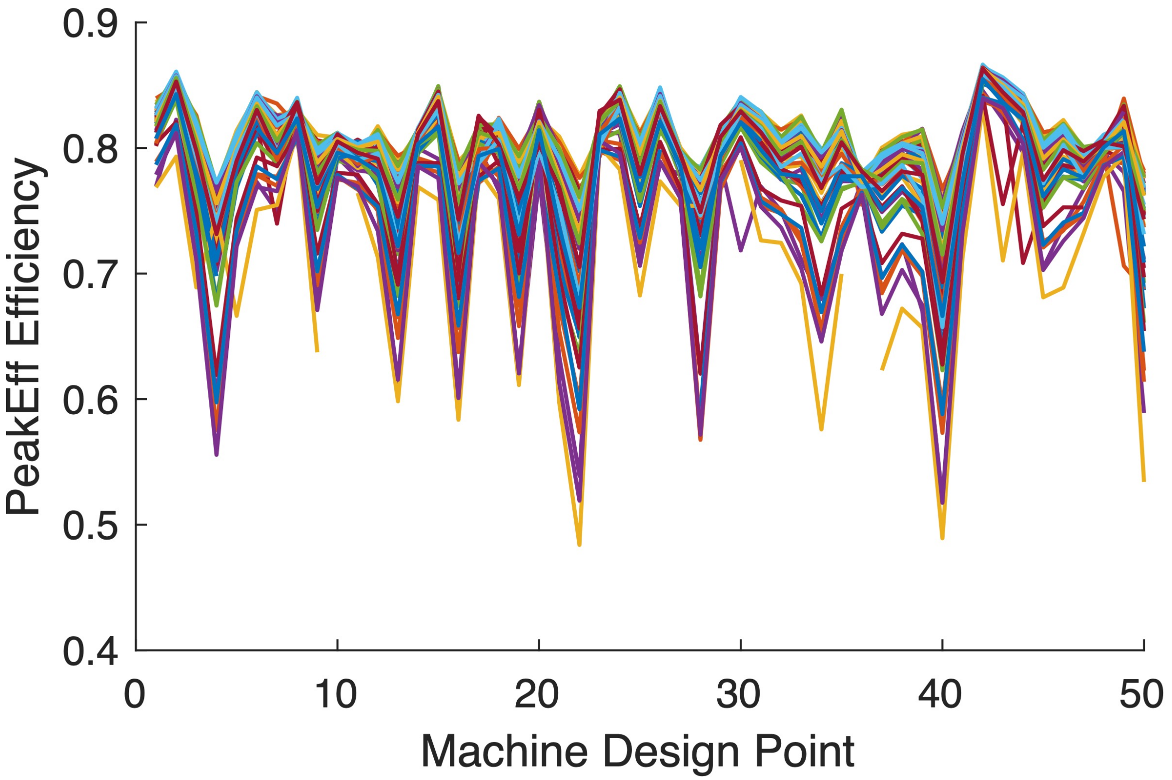
NESTED DESIGN OF EXPERIMENTS

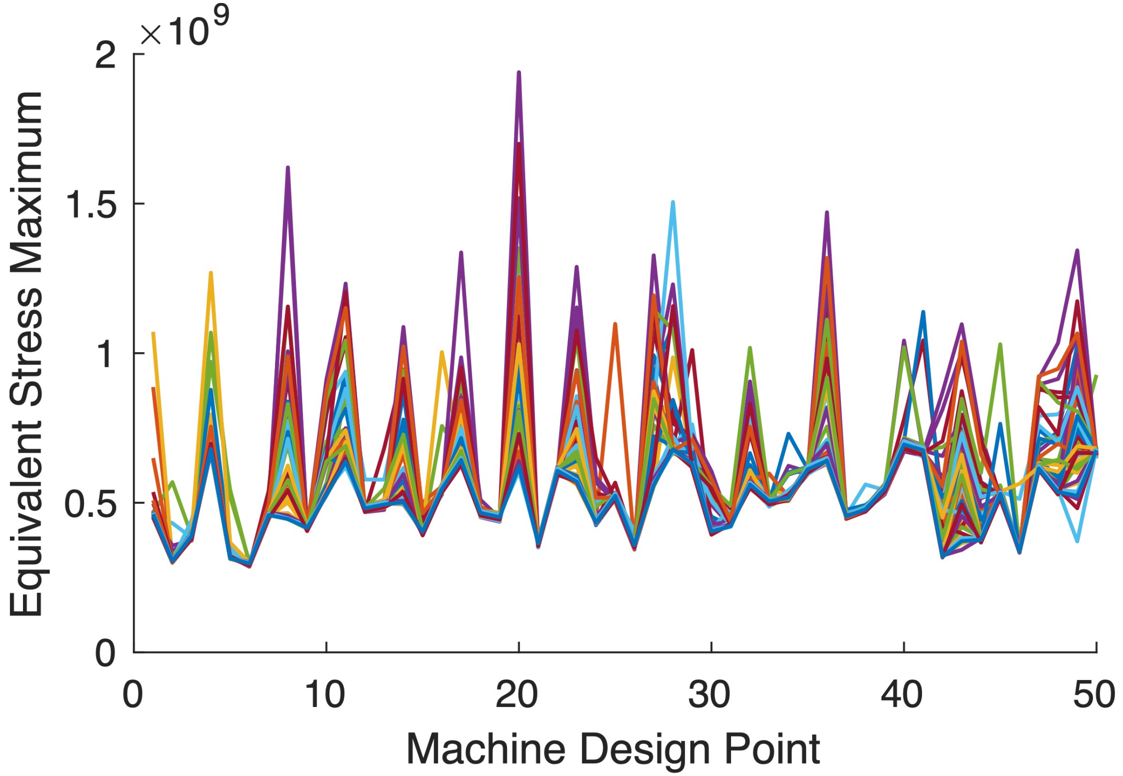
Solving

- CFD
  - 2481 / 2500 successfully computed speed lines
  - More than 19 TB of data
  - More than 35.000 CFD simulations
  - Computational time around 6 months
- FEA
  - All 2500 designs were successfully computed
  - 2.7 TB data

NESTED DESIGN OF EXPERIMENTS

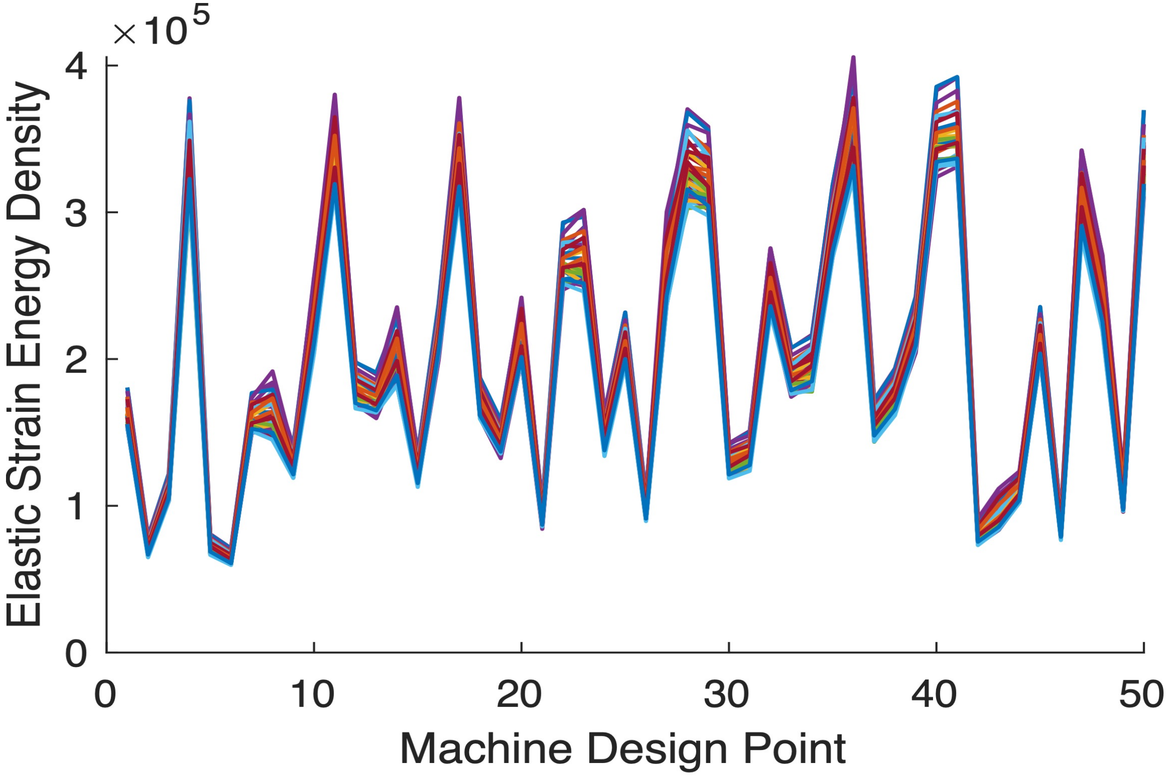
Initial result evaluation

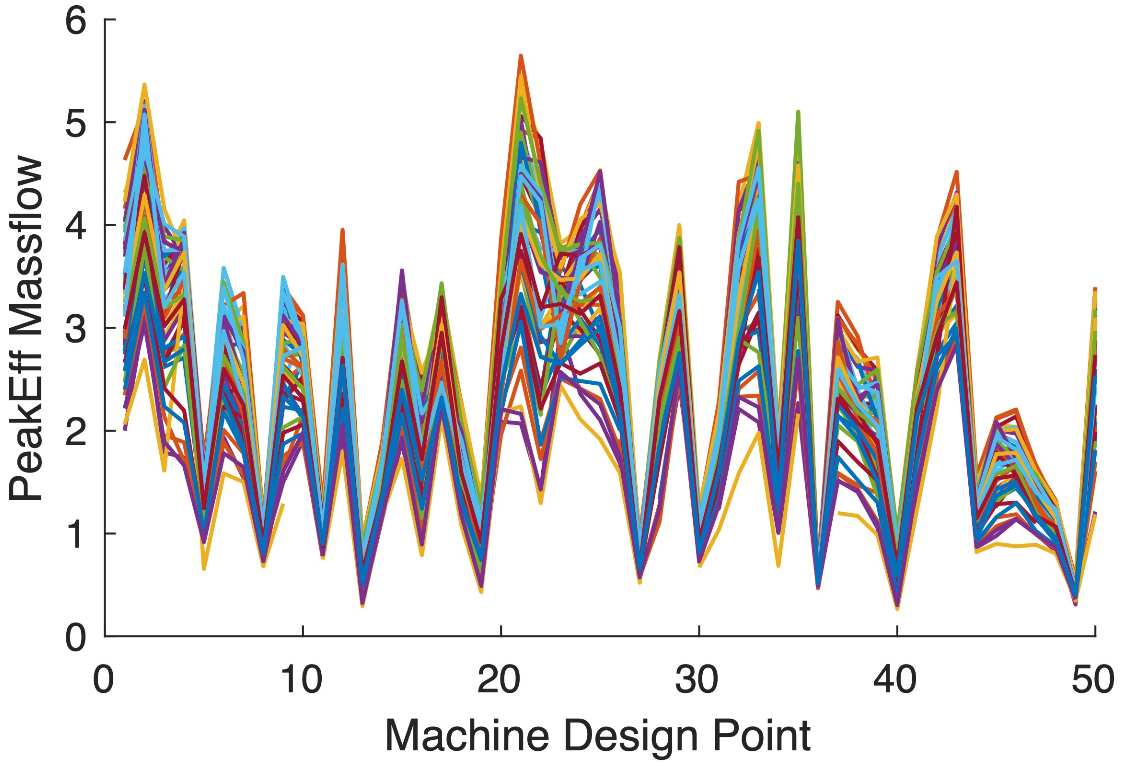




NESTED DESIGN OF EXPERIMENTS

Initial result evaluation



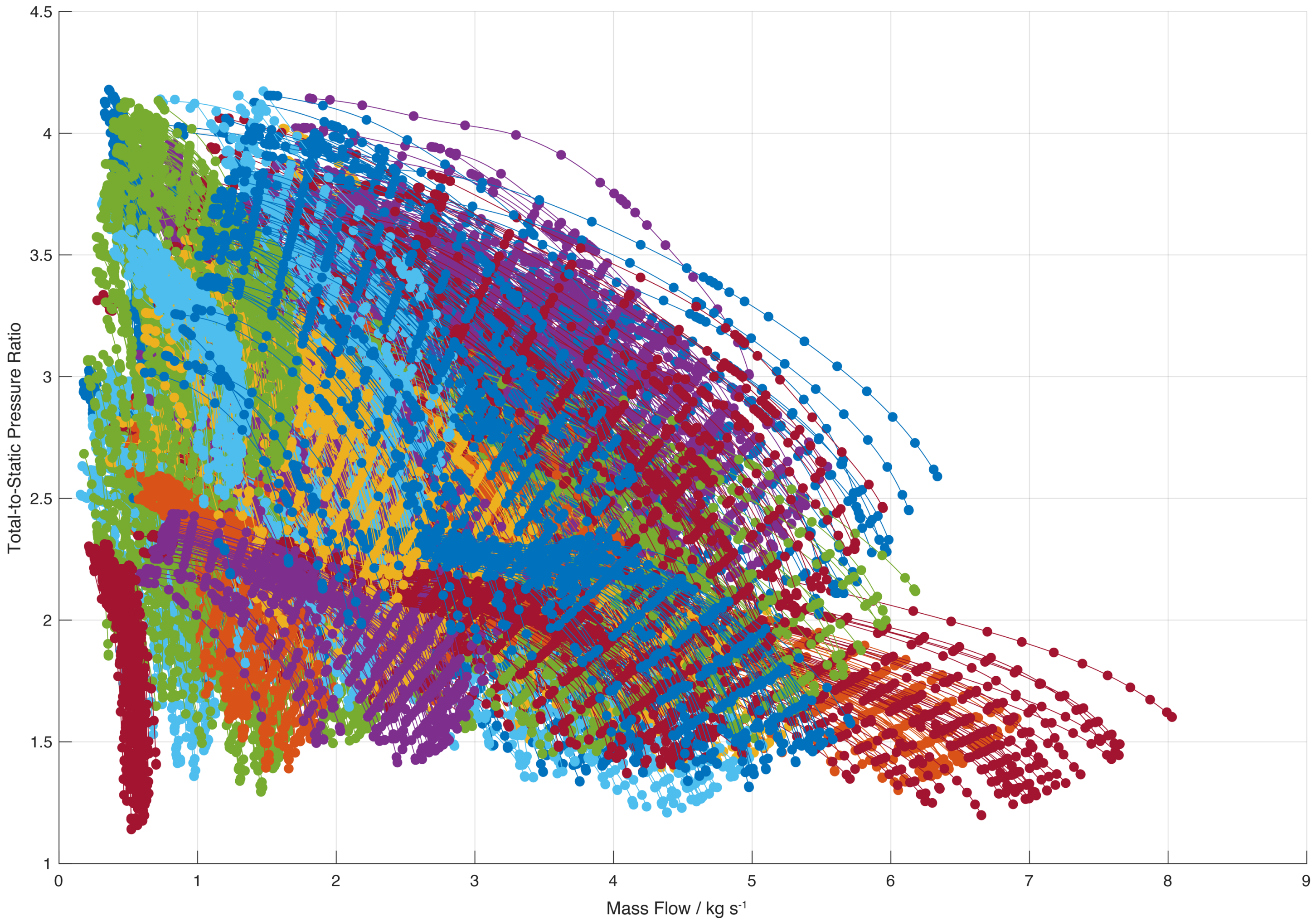


1. Introduction
2. Computational Model
3. Nested Design of Experiments
4. **Surrogate Modeling**
5. Applications

SURROGATE MODELING

Speed line interpolation

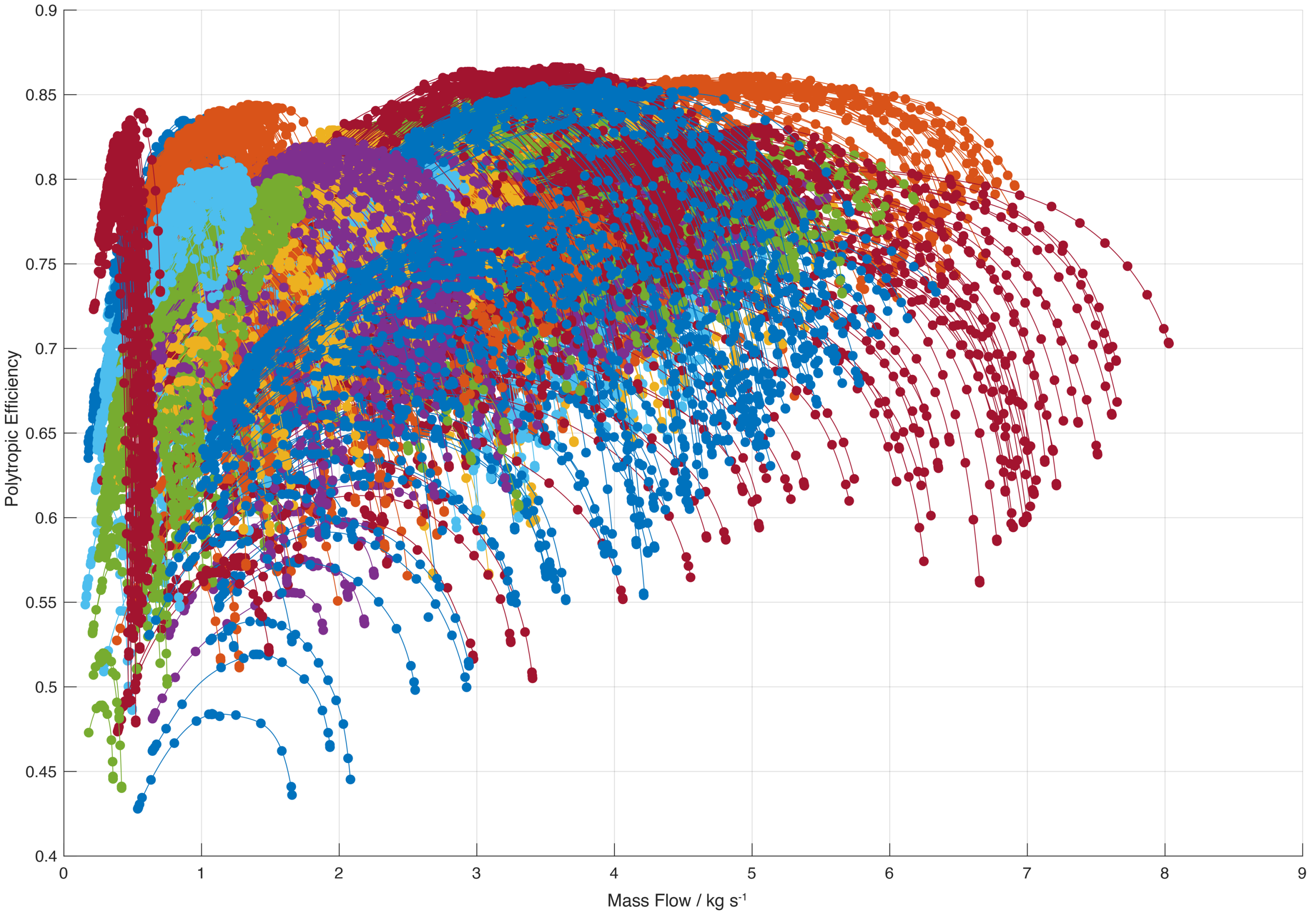
- Modeled as function of exit-corrected mass flow rate:
  - **Mass flow rate**
  - **Total-to-static pressure ratio**
  - Polytropic efficiency
- Additionally, spline fitting was conducted



SURROGATE MODELING

Speed line interpolation

- Modeled as function of exit-corrected mass flow rate:
  - **Mass flow rate**
  - Total-to-static pressure ratio
  - **Polytropic efficiency**
- Additionally, spline fitting was conducted



SURROGATE MODELING

Geometry design of experiments

- Inputs: Geometry design parameters
- Outputs:

Parameter	Symbol	Unit
Speed line parameters		
Peak efficiency	$\eta_{\mathrm{pol}_{\max}}$	–
Peak efficiency mass flow rate	$\dot{m}_{\eta-\max}$	$\mathrm{kg\,s^{-1}}$
Peak efficiency total-to-static pressure ratio	$\Pi_{\mathrm{t-s}_{\eta-\max}}$	–
Choke efficiency	$\eta_{\mathrm{pol}_{\mathrm{choke}}}$	–
Choke mass flow rate	$\dot{m}_{\mathrm{choke}}$	$\mathrm{kg\,s^{-1}}$
Choke total-to-static pressure ratio	$\Pi_{\mathrm{t-s}_{\mathrm{choke}}}$	–
Surge efficiency	$\eta_{\mathrm{pol}_{\mathrm{surge}}}$	–
Surge mass flow rate	$\dot{m}_{\mathrm{surge}}$	$\mathrm{kg\,s^{-1}}$
Surge total-to-static pressure ratio	$\Pi_{\mathrm{t-s}_{\mathrm{surge}}}$	–
Normalized speed line width	$\Delta\dot{m}_{\mathrm{norm}}$	–
Total-to-static pressure ratio spline parameter ($\dot{m}$-coordinate)	$\chi_{\mathtt{TSPR}_{\dot{m}}}$	–
Total-to-static pressure ratio spline parameter ($\Pi_{\mathrm{t-s}}$-coordinate)	$\chi_{\mathtt{TSPR}_{TSPR}}$	–
Polytropic efficiency spline parameter ($\dot{m}$-coordinate)	$\chi_{\mathtt{Eff}_{\dot{m}}}$	–
Polytropic efficiency spline parameter (η_{pol}-coordinate)	$\chi_{\mathtt{Eff}_{\dot{\eta}}}$	–

Structural load parameters		
Maximum value of the von Mises stress	$\sigma_{v_{\max}}$	Pa
Maximum value of the deformation	$\Delta\mathbf{X}_{\max}$	m
Directional deformation of the leading edge at the shroud, collinear	Δb_{LE}	m
Directional deformation of the trailing edge at the shroud, collinear	Δb_{TE}	m
Elastic strain energy of the full impeller model	U_{impeller}	J
Elastic strain energy of the blade region	U_{blade}	J
Elastic strain energy of the disc region	U_{disc}	J
Elastic strain density of the full impeller model	u_{impeller}	$\mathrm{J\,m^{-3}}$
Elastic strain density of the blade region	u_{blade}	$\mathrm{J\,m^{-3}}$
Elastic strain density of the disc region	u_{disc}	$\mathrm{J\,m^{-3}}$
Volume of the full impeller model	V_{impeller}	$\mathrm{m^3}$
Volume of the blade region	V_{blade}	$\mathrm{m^3}$
Volume of the disc region	V_{disc}	$\mathrm{m^3}$

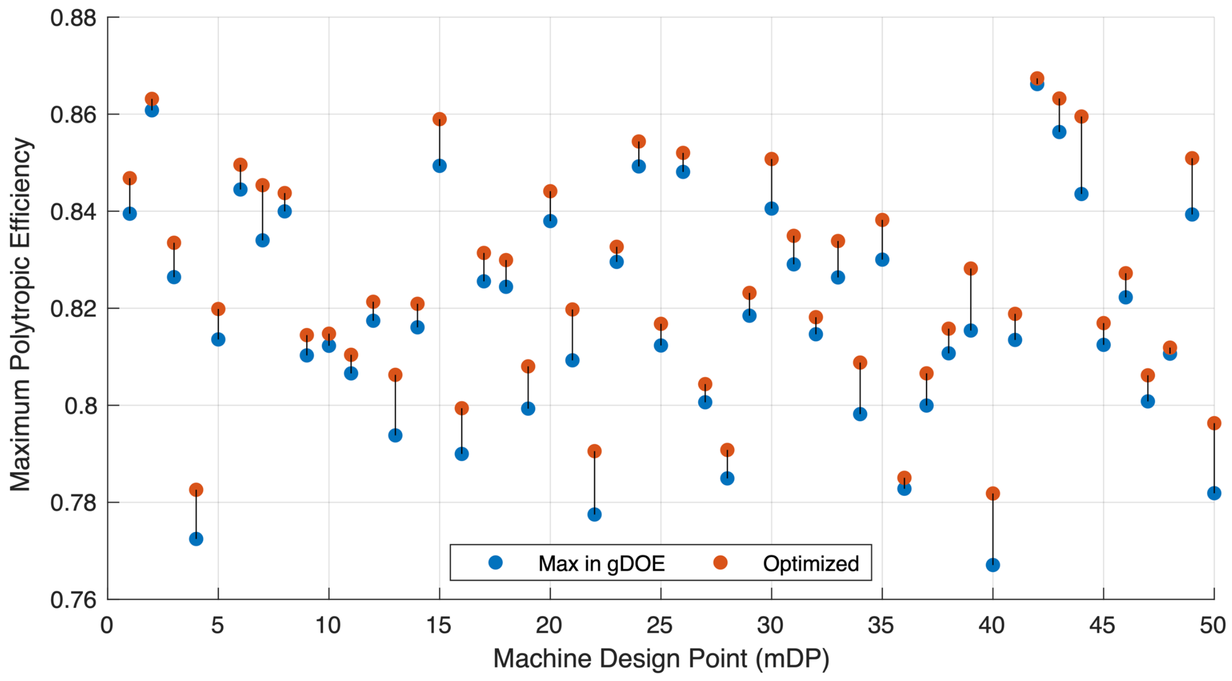
SURROGATE MODELING

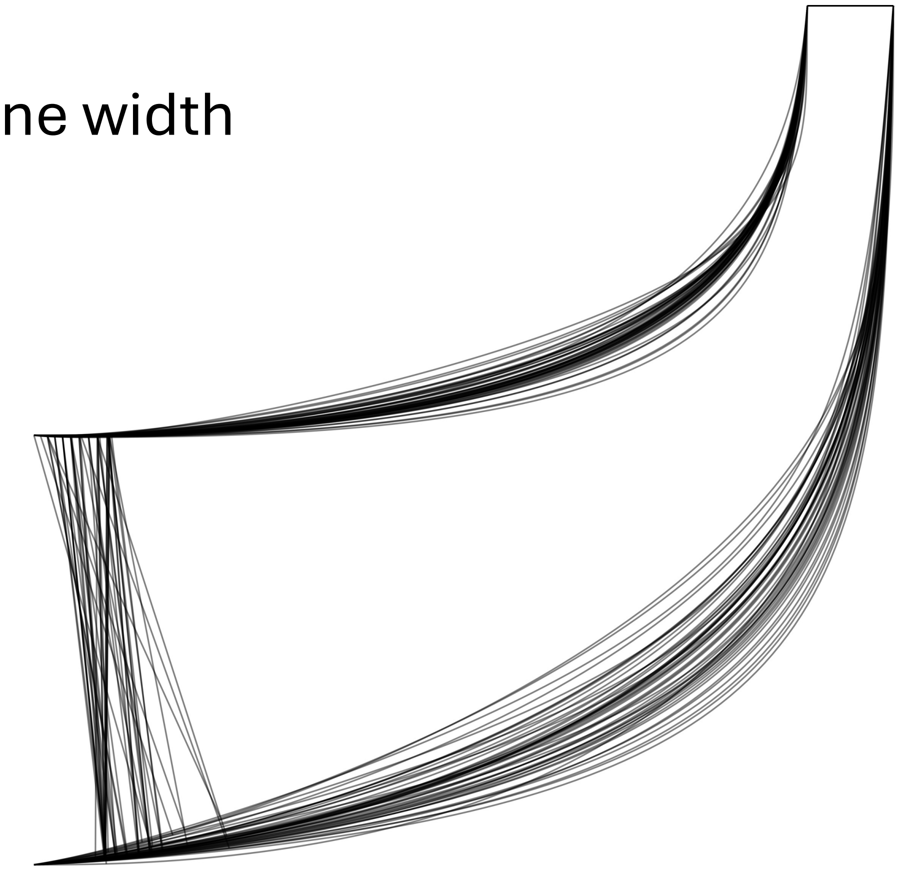
Geometry design of experiments

- Hybrid surrogate model is trained 50 times (each machine design point) for each output parameter = 1350 surrogate models
- Mean WR2 = 0.9483

Machine design point-wide optimization

- Optimization of geometry design parameters for each machine design point:
  - Achievable efficiency and achievable speed line width





SURROGATE MODELING

Machine design of experiments

Inputs:

Sampled:

- Ambient volume flow rate
- Total-to-static pressure ratio
- Axial impeller extent ratio
- Circumferential blade extent
- Impeller exit relative blade angle

Derived:

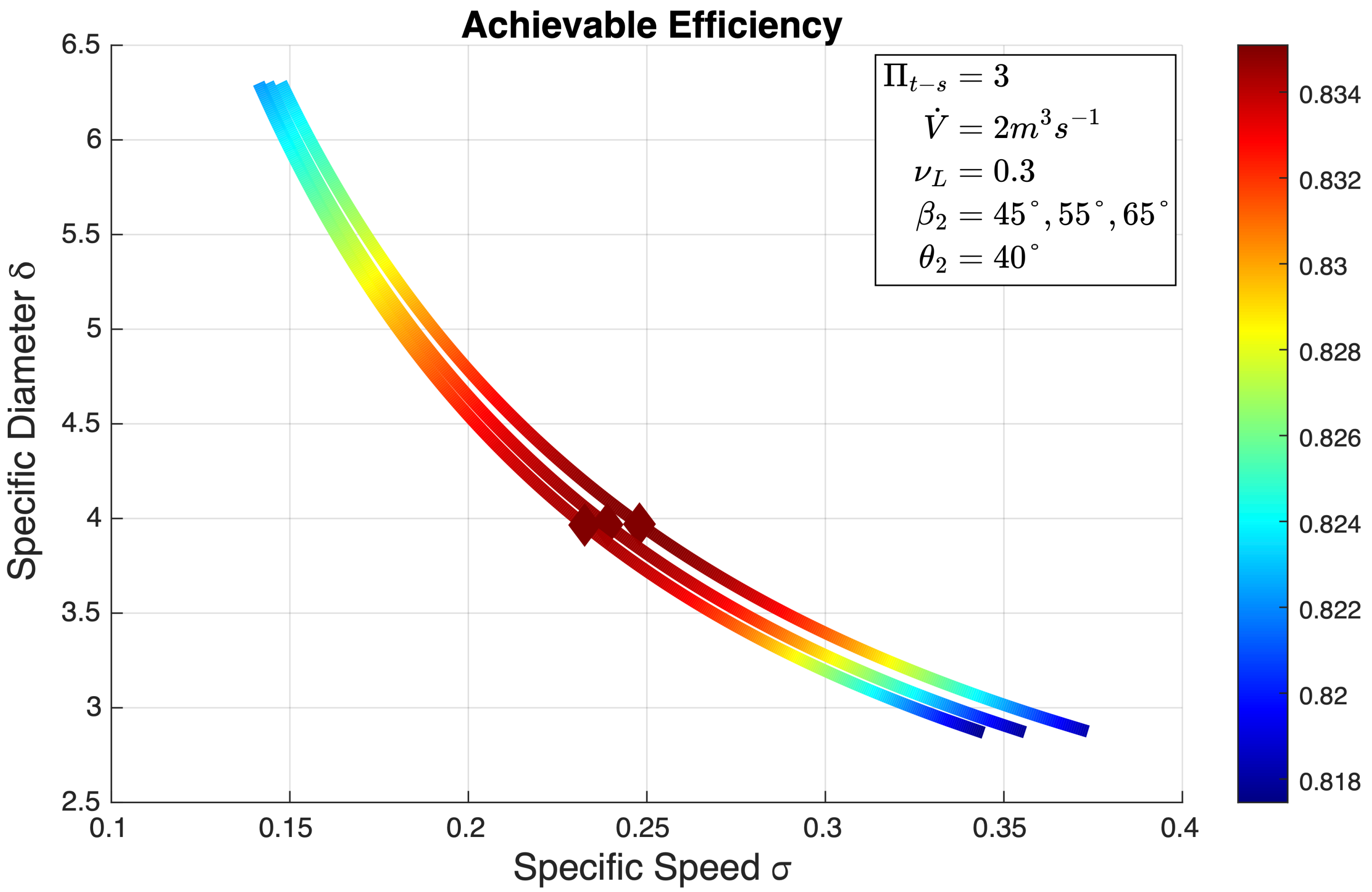
- Specific diameter
- Specific speed
- Flow coefficient
- Polytropic work coefficient
- Chord Reynolds number

- Outputs:
  - Achievable Efficiency
  - Achievable Speed Line Width
  - Associated speed line parameters
  - Associated geometry parameters
  - Machine design point-wide structural result parameters
- WR2 for main parameters > 0.99

1. Introduction
2. Computational Model
3. Nested Design of Experiments
4. Surrogate Modeling
5. Applications

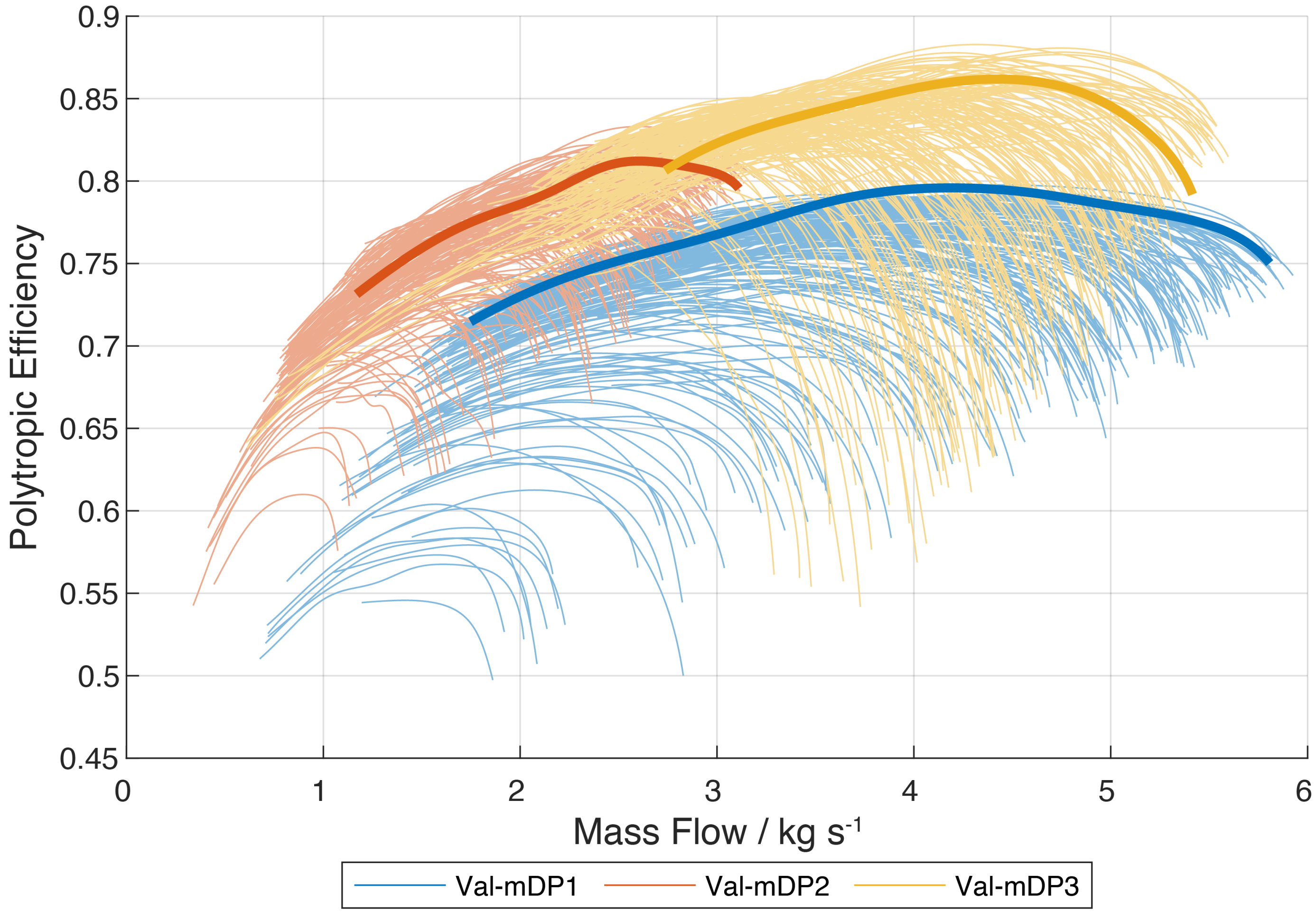
RESULTS

Duty-specific Cordier lines



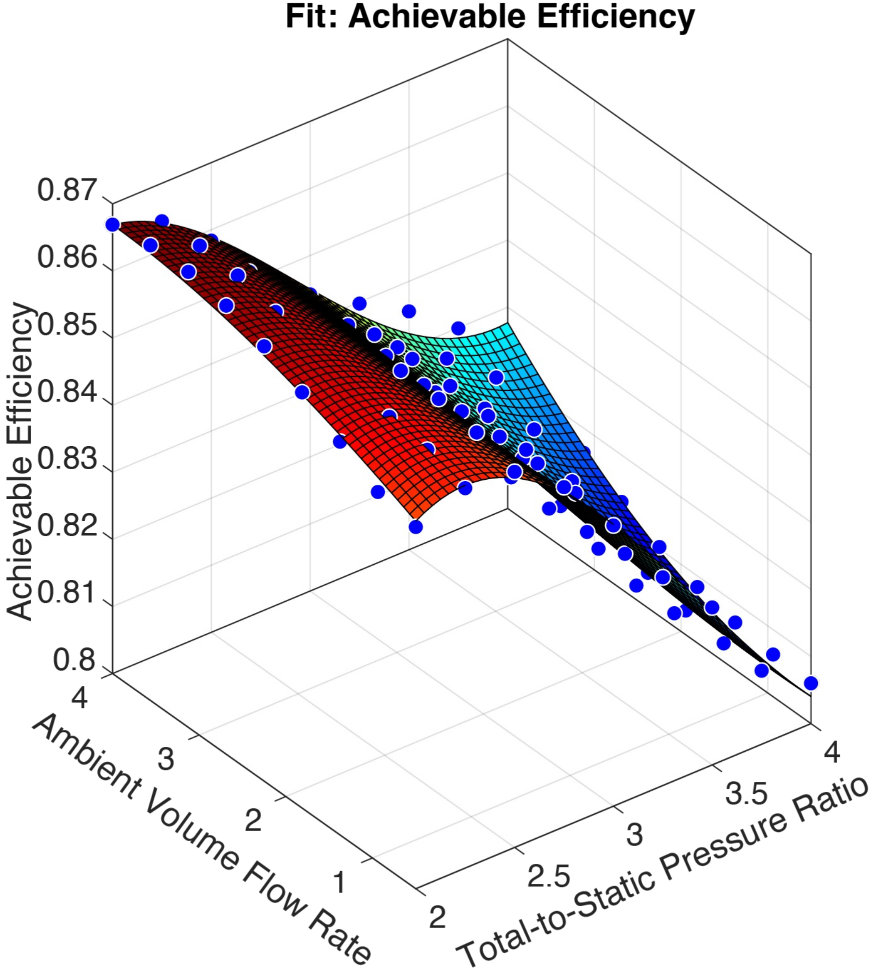
RESULTS

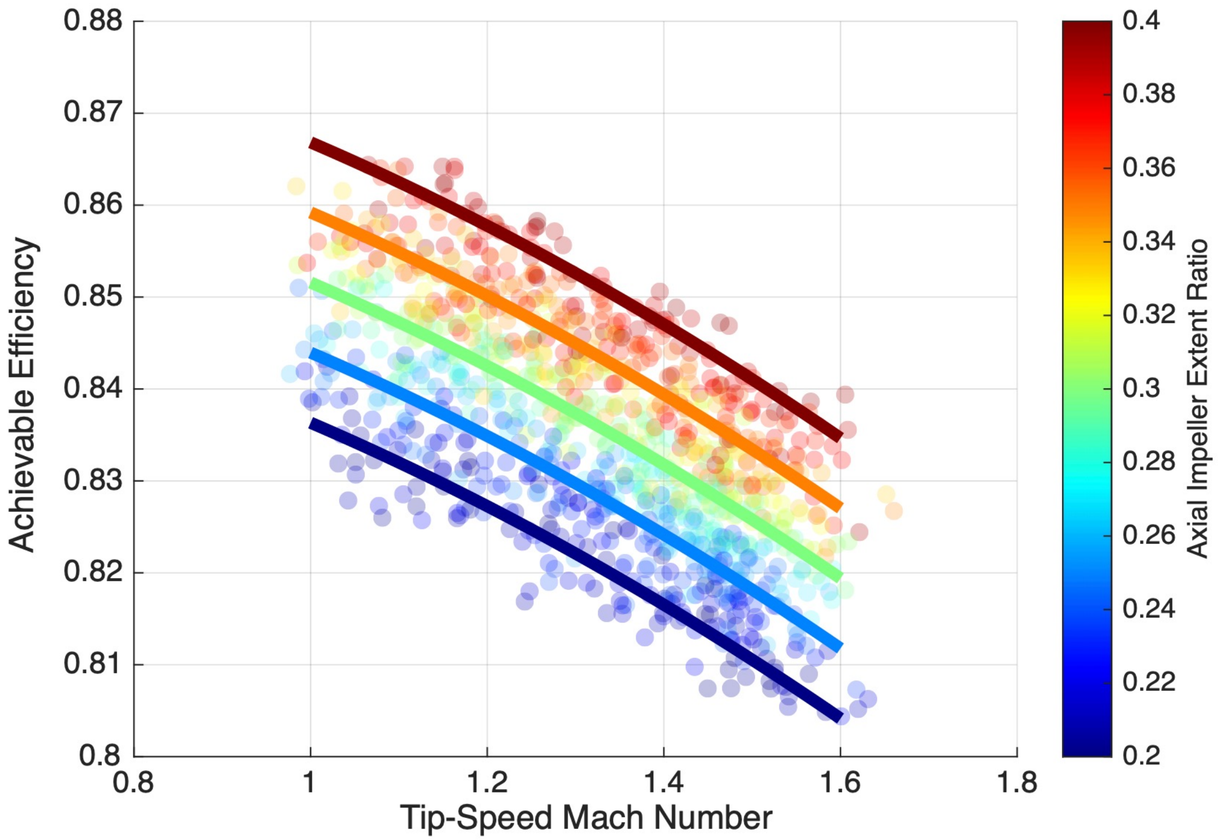
Direct optimization, initial guess for impeller geometry



RESULTS

Efficiency correlations





Modelling of Multi-Parameter-Level Simulation Data to Create an Enhanced Cordier Diagram for Radial Turbocompressors

THANK YOU

iSimT-24 Symposium on Innovative Simulations in Turbomachinery

Yannick Lattner, M.Eng

Team Lead CFD at ITB Ingenieurgesellschaft für technische Berechnungen